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**USNCTAM2010-1383****COMPARISON OF MECHANICAL AND CONSTITUTIVE RESPONSE FOR FIVE ALUMINUM ALLOYS FOR ARMOR APPLICATIONS****Kathryn A. Dannemann, Sidney Chocron, Charles E. Anderson, Jr.**

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**ABSTRACT**

There is heightened interest in aluminum alloys for armor applications owing to their low density and reasonable cost compared to alternative metallic armor materials. Five aluminum alloys of interest for vehicle armor applications were evaluated: Al5083-H131, Al5059-H131, Al2139-T8, Al2195-BT and Al2519-T87. The mechanical performance of these five alloys was assessed and compared, based on the results of mechanical characterization tests. The experimental data obtained for each alloy were used to determine constitutive constants for Johnson-Cook strength and failure models. The constitutive constants obtained were validated using numerical simulations and the results of Taylor impact experiments.

**INTRODUCTION**

The objective of this extensive characterization effort was to develop the Johnson-Cook (J-C) constitutive model (including strength and failure) for the five aluminum (Al) alloys of interest. Material constitutive models are critical for effective numerical simulations and analyses of high speed ballistic events. The J-C model is an empirical model, developed in the eighties, to describe the constitutive behavior of materials [1,2]. Although other physical models have been developed since its introduction, it is widely used for such applications owing to its relevance, ease of use and ease of determining constants from mechanical test data.

Several other aluminum alloys have been characterized previously for determination of J-C constitutive parameters [3,4]. However, the accuracy of numerical predictions for armor design and evaluation is dependent on the use of representative constitutive models. Hence, J-C constitutive constants were determined for the specific Al alloy (and temper) of interest. Different tempers of the same alloy may exhibit different responses owing to changes in microstructure and response due to different tempering treatments.

**MATERIALS**

Five different aluminum alloys were characterized in this study. These include three 2000 series alloys (Al2139-T8, Al2195-BT and Al2519-T87) and two 5000 series alloys (Al5083-H131, Al5059-H131). All mechanical test specimens were obtained from 25-mm thick Al plates. The plates were provided with the desired temper. Copper is the primary alloying element in the 2000 series Al alloys, while magnesium is the primary alloying element in Al 5000 series alloys.

The 2000 series alloys can be strengthened by heat treatment. The T8 and T87 tempers indicate solution heat treatment, followed by cold work and artificially aging. BT indicates a balanced temper. This temper was developed for resisting specific threats [5]. Alloys in the 5000 series are non-heat treatable; strength is developed by solid solution hardening or by strain hardening from the annealed temper. The H131 temper is applicable to armor plate, and differs from the H116 marine grade temper for which characterization results are available in the literature for Al 5083-H116 [4].

**EXPERIMENTAL**

Mechanical characterization tests were conducted on each alloy of interest. Although aluminum alloys are generally strain rate insensitive, experimental data were obtained to determine the strain rate and thermal terms for these specific alloys/tempers as these effects are included in the Johnson-Cook constitutive model. The types of tests conducted include: smooth and notched tension at two different low strain rates, torsion tests at three different strain rates, and dynamic tension and compression tests performed at two different high strain rates ( $\sim 10^2 \text{ s}^{-1}$ ,  $10^3 \text{ s}^{-1}$ ) using a split Hopkinson pressure bar (SHPB). The SHPB compression tests were conducted at room temperature, and two different elevated temperatures (160°C and 320°C).

Taylor impact tests were also performed as a means of validating the constitutive constants obtained. These tests were

performed at velocities ranging from approximately 80 m/s to 400 m/s. Validation was accomplished through performance of numerical simulations of the Taylor impact test using the constitutive constants obtained.

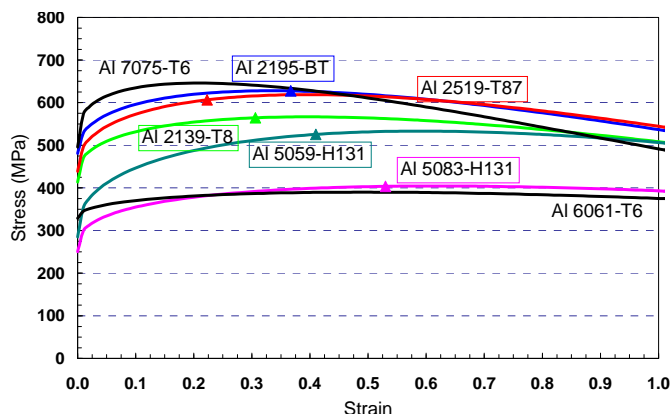
All specimens were oriented in the long-transverse direction (i.e., the long axis of the specimen was in the plane of the plate, and oriented perpendicular to the rolling direction). Since the program could accommodate testing in only one direction, the long-transverse (LT) direction was chosen as a conservative measure of the properties. Properties in the LT direction are generally lower than for the rolling direction. Johnson-Cook constants for each aluminum alloy were determined based on averaged test results for each test type.

## RESULTS

Experimental results for each test type were compared for the five Al alloys. Generally, the 2000 series alloys exhibited higher tension and torsion strengths. The failure strains differed among the alloys. Higher shear strains were measured for the 5000 series alloys.

Strain rate effects were assessed upon comparison of the SHPB test results with the lower strain rate tensile test results. Strain rate strengthening effects were small for these Al alloys. Temperature effects were determined based on SHPB compression tests at elevated temperature (160C, 320C).

Johnson-Cook strength and damage constants were determined for each alloy of interest. The J-C strength constants differed for the tension vs. torsion data obtained. Average constants were used for alloy comparisons, and were determined by averaging the values of the constants obtained for the tension and torsion data. The average constants were used to derive adiabatic stress-strain curves for each alloy, as shown in Figure 1. These curves include the effects of strain hardening and thermal softening. This allows a direct comparison of the strength of different materials for conditions similar to impact. The curves in Figure 1 were determined at a strain rate of  $1500 \text{ s}^{-1}$ .



**FIGURE 1. COMPARISON OF ADIABATIC STRESS-STRAIN CURVES (at  $1500 \text{ s}^{-1}$ ) FOR THE FIVE ALLOYS EVALUATED VERSUS AL 6061-T6 AND AL 7075-T6. FAILURE STRAINS ARE INDICATED BY THE SYMBOL ON EACH CURVE.**

Numerical simulations of the Taylor anvil tests, using the J-C constants derived from the test data for each Al alloy, showed good agreement with the test results. This validated the J-C constants obtained for each alloy.

## CONCLUSIONS

The Johnson-Cook constitutive constants were determined for each of the five aluminum alloys using the mechanical test data. The test results indicate high tension and torsion strengths for the 2000 series alloys evaluated: Al 2195-BT, Al 2139-T8, Al 2519-T87. The results were also compared in terms of energy, estimated using the area under the stress-strain curves and the failure strain for each alloy. These comparisons highlight the benefits of Al2195-BT and Al5083-H131 versus Al 2519-T87 and Al 5059-H131. However, the beneficial effects of energy absorption cannot be realized if the alloy strength is insufficient. The laboratory test results for these five alloys agree with the observed ballistic response: 2000 series alloys show superior performance versus 5000 series alloys.

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